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FLOOD FREQUENCIES DERIVED FROM RIVER FORECASTING PROCEDURES

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HYDRAULICS DIVISION

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FLOOD FREQUENCIES DERIVED FROM RIVER FORECASTING PROCEDURES

Ralph F. Kresge[1] and Tor J. Nordenson[2],
Associate Members, ASCE

ABSTRACT

The engineer in the design of culverts, bridges, and other drainage structures has to estimate the peak annual discharge expected for some selected return period or periods. Such estimates often are based on frequency analyses of relatively short discharge records and, therefore, the reliability of the estimates is questionable. In the study reported here, the record of peak annual discharge values was extended through use of precipitation data and a river forecasting procedure. The differences between the frequency curves based on observed and estimated flood peaks were small and were far less than the differences between frequency curves developed from segments of the observed record.

PURPOSE OF STUDY

The purpose of this study is to demonstrate the feasibility of using long-term precipitation observations to extend runoff records in order to develop more reliable annual peak discharge frequency curves. In the design of bridges, culverts and drainage structures an important factor to be considered is the reliability of the flood-frequency analysis. For example, a more accurate estimate of the magnitude of a 10-year flood (recurrence interval 10 years) could be obtained from a 50-year than from a 10-year discharge record. An accepted method of treating a short-term record is to make a frequency analysis using techniques developed by Foster, Hazen, Gumbel or others. The method used in this study is to extend the period of discharge record by the use of long-term precipitation records and river-forecasting procedures and then making a frequency analysis based upon the observed and extrapolated record.

INTRODUCTION

The Weather Bureau has precipitation-runoff relations and related procedures for estimating flood peaks for a major portion of the country. These procedures have been developed in connection with its river-forecasting program. The procedures are directly applicable to the extrapolation of streamflow records in areas where precipitation data cover a longer period than streamflow data. The error in estimating individual flood peaks may be as great as 20%, but the effect of such errors on derived frequency curves is minor, provided the errors are random. The discharge records of the

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Hocking River at Athens, Ohio, were selected for this study. Maximum annual flood peaks were estimated for the full period of streamflow record (37 years) and frequency curves were derived from both the observed and estimated peak values. The differences between the frequency curves based on observed and estimated flood peaks were small and were far less than the differences between frequency curves developed from segments of the observed record. Additional tests should be made before definite conclusions can be reached, but this study indicates that errors in individual flood peak estimates do not materially affect the derived frequencies.

Procedure

Selection of Basin for Analysis

Selection of a river basin for this study was dependent not only upon the availability of a long period of discharge records, but equally important was the need to select an area for which a modern flood-forecasting procedure was already available. This second condition was considered important only for the sake of expedience. The criteria for selection of the basin to be analyzed are listed below:

1. Reliable discharge records of at least 35-40 years in length.
2. Flood-forecasting procedure available (preferably a headwater basin requiring only a unit hydrograph and a rainfall-runoff relation).
3. Adequate long-record precipitation stations located within the drainage basin.

The selection was restricted to a headwater basin in order to avoid the more complex forecasting procedures involving flood routing.

The basin selected is that above the USGS gaging station on the Hocking River at Athens, Ohio, which has a drainage area of 944 square miles. Flow records for the 37-year period, 1915 through 1951, were analyzed. Location of drainage basin and precipitation stations is shown on Figure 1. The maximum annual peak discharge ranges from 7,000 to 30,000 CFS.

Description of Flood Forecasting Procedures

The forecasting relations for this area were developed by the staff of the Weather Bureau River Forecast Center located at Cincinnati, Ohio, the office responsible for the preparation of daily river and flood forecasts for most of the Ohio River Basin. Basically, the method consists of computing the total volume of surface runoff associated with a particular combination of storm rainfall and antecedent weather factors and distributing this runoff in time by means of the unit hydrograph.

The technique used in computing runoff from storm rainfall was developed by Kohler and Linsley and is described in Weather Bureau Research Paper No. 34. Briefly, the procedure consists of a coaxial graphical correlation analysis relating storm runoff to antecedent precipitation index, season or week of year, storm duration and storm rainfall. A reliable rainfall-runoff relation can usually be developed using 5 to 10 years of precipitation and runoff data. The rainfall-runoff relation used is shown in Figure 2 and was developed from 11 years of data (1940-1950).

The next step, the distribution of runoff with respect to time according to the characteristics of the drainage area, was accomplished by the application of the unit hydrograph principle. ("Streamflow from Rainfall by the Unit Graph Method", by L. K. Sherman, Engineering News-Record, p. 501, 1932.)

The 12-hour unit hydrograph used in this analysis is shown in Figure 3. A 6-hour unit hydrograph would probably slightly improve the accuracy of the peak flow forecasts, especially over the last 10 years of record, when hourly precipitation data are available. Estimates of 6-hourly precipitation amounts could not be made with reasonable accuracy for the earlier precipitation records, whereas 12-hourly estimates were feasible; therefore, to be consistent, a 12-hour unit hydrograph was used for the entire period.

The peak discharge is, of course, a combination of surface runoff and base flow. In the practical application of this technique, base flow values would have to be estimated for the period of extrapolated record. In order to simulate actual conditions a method was devised to estimate base flow. Using observed discharge data for the past few years, it was possible to determine a relationship between base flow and antecedent index (Figure 4). Antecedent index is the value obtained from the first quadrant of the rainfall-runoff relation (see Figure 2) as the combined effect of antecedent precipitation index and week of the year. The value of base flow varies between 200 and 2000 c.f.s. (approximately) and, therefore, errors in estimating this flow would have a minor effect on the computation of the total peak discharge.

Computed Peak Annual Flood Discharges

A tabulation of the observed maximum annual peak discharges for the period of record - 1915 through 1951 - is shown in Table 1. The annual peak discharges computed by means of the flood forecasting procedures are also listed. It will be noted that in several instances the date of the observed and computed peak discharges do not coincide. In several cases this is undoubtedly due to an error in timing of certain increments of runoff resulting from variable rainfall intensity, or uneven distribution of rainfall over the basin, or other well-known limitations of the unit-hydrograph method. In addition to these factors, even a 10% error in estimating surface runoff can occasionally account for the difference in date of computed and observed peak annual discharge.

Frequency Analyses

The method used to perform the frequency analysis of the maximum annual peak discharges was that described by Gumbel*, and later amplified**. In the application of this theory, floods are tabulated in order of magnitude, starting with the lowest flood record as serial number 1. (See Table 2.)

Separate frequency analyses were made based on the observed and computed maximum annual peak discharges using data for the full 37 years of record. These frequency curves are shown in Figure 5. It is evident that the two curves are in close agreement, with the computed data curve yielding slightly less discharge per return period than the observed data curve. This error, ranging from 5% for the 5-year return period to 2% for the 37-year return period, is considered reasonable. Next, the data were arbitrarily divided into two periods of 18 years, 1916-1933 and 1934-1951, in order to illustrate

* Gumbel, E. J., On the Plotting of Flood Discharges, Trans. Am. Geophys. Union, Vol. 24, Part D, pp. 699-719, 1943.

** Evaluation of Climatic Extremes, Environmental Protection Section Report No. 175, Research and Development Branch, Military Planning Division, Office of the Quartermaster General, March 1951.

TABLE 1

OBSERVED AND COMPUTED MAXIMUM
ANNUAL PEAK DISCHARGES
HOCKING R.
ATHENS, O.

Year	Mo/Day	Observed Discharge (1000 cfs)	Mo/Day	Computed Discharge (1000 cfs)
1951	1/16	22.4	1/15	17.0
1950	1/8	13.2	1/7	16.0
1949	1/29	10.7	1/28	8.9
1948	4/13	25.5	4/14	28.4
1947	2/1	8.0	1/31	8.4
1946	6/20	10.6	6/19	11.7
1945	3/7	30.4	3/7	27.5
1944	3/8	11.2	3/8	12.7
1943	3/21	20.0	3/20	19.6
1942	12/31	12.6	12/30	13.7
1941	6/4	15.2	6/4	15.6
1940	4/21	30.0	4/20	28.3
1939	4/17	15.5	4/18	15.6
1938	5/25	14.6	5/23	15.9
1937	1/23	33.2	1/23	28.0
1936	4/7	13.1	4/7	11.0
1935	9/5	17.3	5/3	13.1
1934	3/4	8.3	3/5	7.3
1933	5/15	18.0	5/15	16.2
1932	1/30	6.7	1/31	8.8
1931	4/5	11.2	4/4	12.4
1930	3/9	11.7	3/9	11.8
1929	11/19	11.0	2/29	6.4
1928	6/22	13.4	6/21	8.8
1927	1/22	13.6	1/23	13.3
1926	8/19	12.0	8/19	7.4
1925	5/11	8.5	5/12	4.7
1924	3/30	14.1	3/30	15.0
1923	12/23	10.7	12/23	9.8
1922	4/16	25.4	4/15	21.1
1921	12/25	17.1	12/25	14.7
1920	4/21	15.8	4/21	17.4
1919	1/2	9.2	1/2	11.1
1918	3/14	12.6	3/14	16.0
1917	1/23	10.9	4/7	11.0
1916	5/8	10.5	1/13	13.5
1915	12/18	12.6	12/18	6.0

the use of short discharge records for depicting the long term frequencies for this station. (See Tables 3 and 4.) The computed and observed frequency curves in Figures 6 and 7 again indicate close agreement. This verification indicates that a river forecasting scheme can provide reliable estimates of peak annual discharges for use in flood frequency analyses.

The frequency curves for the 37-year period and each 18-year period are shown in Figure 8. It is interesting to note that the 1934-51 curve yields considerably higher peak discharges per return period than the 1916-33 curve. Sometimes such a difference might be attributed in part to a time trend which is defined as a change in the relation of runoff to precipitation due to

TABLE 2

FREQUENCY TABULATION
MAXIMUM ANNUAL FLOOD DISCHARGES
HOCKING R., ATHENS, O.

Period 1915-1951

Serial No.	Date (yr)	Observed Discharge (1000 cfs)	Date (yr)	Computed Discharge (1000 cfs)
1	1932	6.7	1925	4.7
	1947	8.0	1915	6.0
	1934	8.3	1929	6.4
	1925	8.5	1934	7.3
5	1919	9.2	1926	7.4
	1916	10.5	1947	8.4
	1946	10.6	1932	8.8
	1949	10.7	1928	8.8
	1923	10.7	1949	8.9
10	1917	10.9	1923	9.8
	1929	11.0	1917	11.0
	1931	11.2	1936	11.0
	1944	11.2	1919	11.1
	1930	11.7	1946	11.7
15	1926	12.0	1930	11.8
	1918	12.6	1931	12.4
	1915	12.6	1944	12.7
	1942	12.6	1935	13.1
	1936	13.1	1927	13.3
20	1950	13.2	1916	13.5
	1928	13.4	1942	13.7
	1927	13.6	1921	14.7
	1924	14.1	1924	15.0
	1938	14.6	1939	15.6
25	1941	15.2	1941	15.6
	1939	15.5	1938	15.9
	1920	15.8	1950	16.0
	1921	17.1	1918	16.0
	1935	17.3	1933	16.2
30	1933	18.0	1951	17.0
	1943	20.0	1920	17.4
	1951	22.4	1943	19.6
	1922	25.4	1922	21.1
	1948	25.5	1945	27.5
35	1937	28.7	1937	28.0
	1940	30.0	1940	28.3
37	1945	30.4	1948	28.4

man-made improvements such as increased water use, soil conservation measures, etc. The close agreement between computed and observed curves for both periods indicates that there is no time trend since the same forecasting procedure was used for the entire period.

To illustrate the most important feature of this study, the supposition is made that there exists only 18 years of discharge record for Athens, and an estimate of the maximum peak discharge expected to recur on an average of every 5, 10, 25, 50 and 100 years is required. Under such circumstances, it is common practice to extrapolate (Gumbel) frequency curves as a straight

TABLE 3

FREQUENCY TABULATION
MAXIMUM ANNUAL FLOOD DISCHARGES
HOCKING R., ATHENS, O.

Period 1934-1951

Serial No.	Date	Observed Discharge (1000 cfs)	Date	Computed Discharge (1000 cfs)
1	2/ 1/47	8.0	3/ 5/34	7.3
2	3/ 4/34	8.3	1/31/47	8.4
3	6/20/46	10.6	1/28/49	8.9
4	1/29/49	10.7	4/ 7/36	11.0
5	3/ 8/44	11.2	6/19/46	11.7
6	12/ 3/42	12.6	3/ 8/44	12.7
7	4/ 7/36	13.1	5/ 3/35	13.1
8	1/ 8/50	13.2	12/30/42	13.7
9	5/25/38	14.6	6/ 4/41	15.6
10	6/ 4/41	15.2	4/18/39	15.6
11	4/17/39	15.5	5/23/38	15.9
12	9/ 5/35	17.3	1/ 7/50	16.0
13	3/21/43	20.0	1/15/51	17.0
14	1/16/51	22.4	3/20/43	19.6
15	4/13/48	25.5	3/ 7/45	27.5
16	1/23/37	28.7	1/23/37	28.0
17	4/21/40	30.0	4/20/40	28.3
18	3/ 7/45	30.4	4/14/48	28.4

line using the same slope as that portion of the curve based upon observed data.

In the actual application of this method, the frequency curve would be based on the combination of the available observed data and the extrapolated values. Accordingly, frequency curves were developed, first using observed data 1934-1951 plus computed values 1915-1933; second, using observed data 1915-1933 plus computed values 1934-1951. These frequency curves were not plotted since they are almost identical to those shown in Figure 6.

Table 5 summarizes the annual peak discharges for 5, 10, 25, 50 and 100-year return periods obtained from the various frequency curves excluding computed curves for 18-year periods. Assuming the curve based upon 37

TABLE 4

FREQUENCY TABULATION
MAXIMUM ANNUAL FLOOD DISCHARGES
HOCKING R., ATHENS, O.

Period 1916-1933

Serial No.	Date	Observed Discharge (1000 cfs)	Date	Computed Discharge (1000 cfs)
1	4/10/32	6.7	5/12/25	4.7
2	5/11/25	8.5	2/29/29	6.4
3	1/ 2/19	9.2	8/19/26	7.4
4	5/ 8/16	10.5	1/31/32	8.8
5	12/23/23	10.7	6/21/28	8.8
6	1/23/27	10.9	12/23/23	9.8
7	11/19/29	11.0	4/ 7/17	11.0
8	4/ 5/31	11.2	1/ 2/19	11.1
9	3/ 9/30	11.7	3/ 9/30	11.8
10	8/19/26	12.0	4/ 4/31	12.4
11	3/14/18	12.6	1/23/27	13.3
12	6/22/28	13.4	1/13/16	13.5
13	1/22/27	13.6	12/25/21	14.7
14	3/30/24	14.1	3/30/24	15.0
15	4/21/20	15.8	3/14/18	16.0
16	12/25/21	17.1	5/15/33	16.2
17	5/15/33	18.0	4/21/20	17.4
18	4/16/22	25.4	4/15/22	21.1

years of observed record as the control and the best possible estimate, it is interesting to compare the accuracy of the return-period values for the 18-year curves and the 37-year curve based upon the computed peak discharges. It is noted, for example, that the peak discharge for the 50-year return period varies from 26.2 to 40.2, based on the 18-year records; the control indicates a value of 32.7 and the computed curve 32.2. For every return period, the maximum annual peak discharge based upon Weather Bureau River Forecasting procedures is more accurate than that based on either 18-year period.

TABLE 5

Period of Record	Return Period - Years				
	5	10	25	50	100
			Observed Data		
1915-1951	20.0	24.0	29.0	32.7	36.5
1934-1951	23.7	28.9	35.2	40.2	45.0
1916-1933	16.7	19.8	23.4	26.2	29.0
			Computed Data		
1915-1951	19.0	23.1	28.3	32.2	36.0
			Combination - Observed and Computed Data		
1934-51 observed 1915-33 computed	20.0	24.2	29.5	33.5	37.4
1934-51 computed 1915-33 observed	19.7	23.6	28.5	32.1	35.8

Conclusion

The study indicated:

1. That a river forecasting procedure can be used to extend the record of peak annual discharge values as shown by the close agreement of the frequency curves based on the 37-year record of observed and computed values.
2. That estimates of peak annual discharge for selected return periods based on the frequency analysis of the 37-year computed data are more reliable than estimates based on analysis of short-record observed data.

This study was undertaken to demonstrate the feasibility of using river forecasting techniques in peak-discharge frequency analysis. A reliable forecasting procedure can be developed from five to ten years of precipitation and discharge data. A headwater area requires only the development of a rainfall-runoff relation and one unit hydrograph; at downstream points, routing procedures and local inflow unit hydrographs would also be needed.

Acknowledgements

The authors are indebted to M. A. Kohler for his assistance and guidance in this study - also W. E. Hiatt, A. L. Shands and others of the Hydrologic Services Division, U. S. Weather Bureau, for their helpful suggestions in the preparation of this paper.

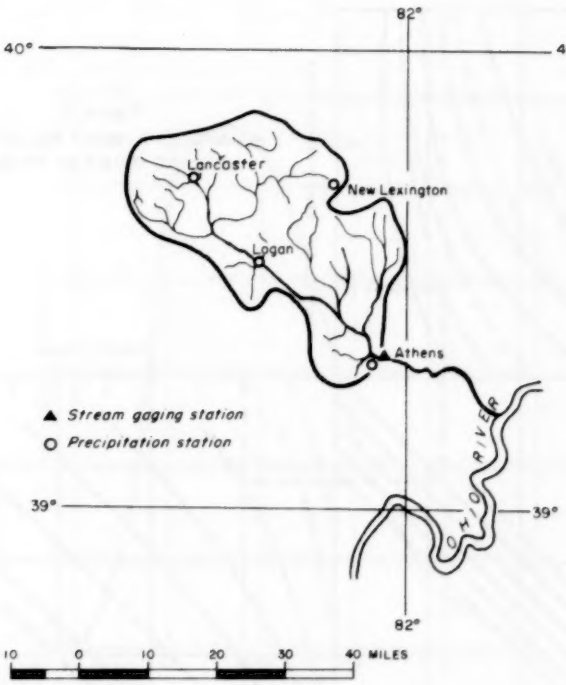

Figure 1
HOCKING RIVER BASIN ABOVE ATHENS, OHIO

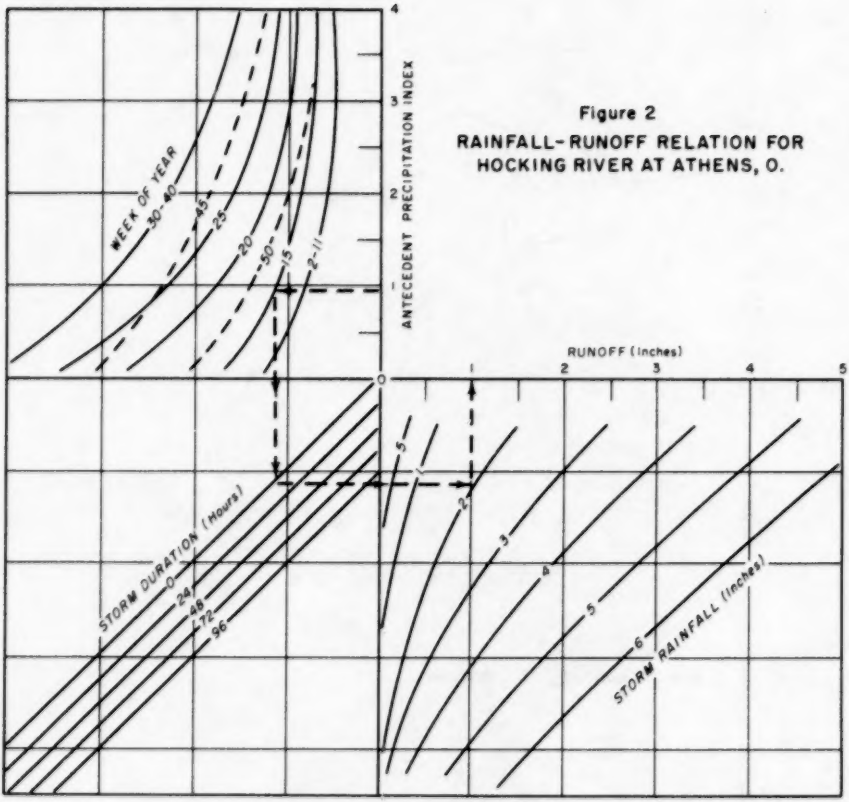

Figure 2
RAINFALL-RUNOFF RELATION FOR
HOCKING RIVER AT ATHENS, O.

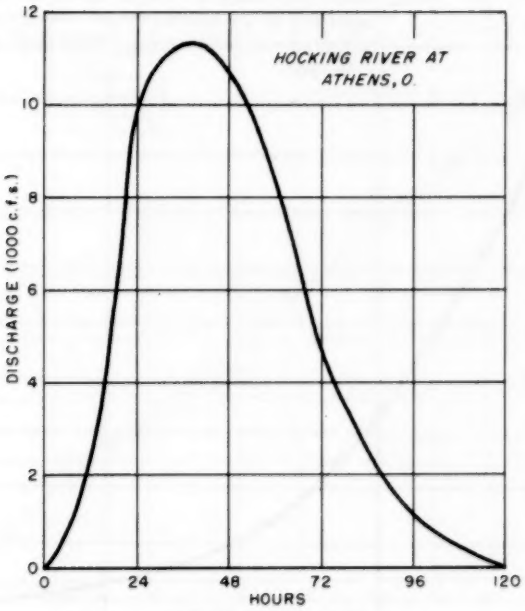

Figure 3 12-HOUR UNIT HYDROGRAPH

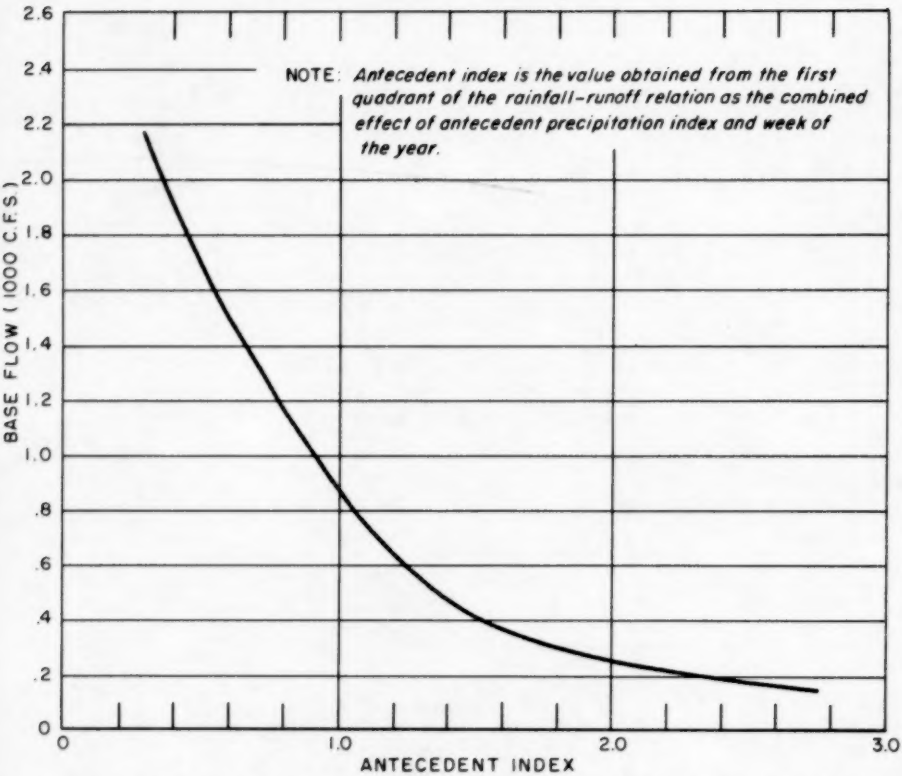

Figure 4. RELATION FOR ESTIMATING BASE FLOW, HOCKING RIVER, ATHENS,O.

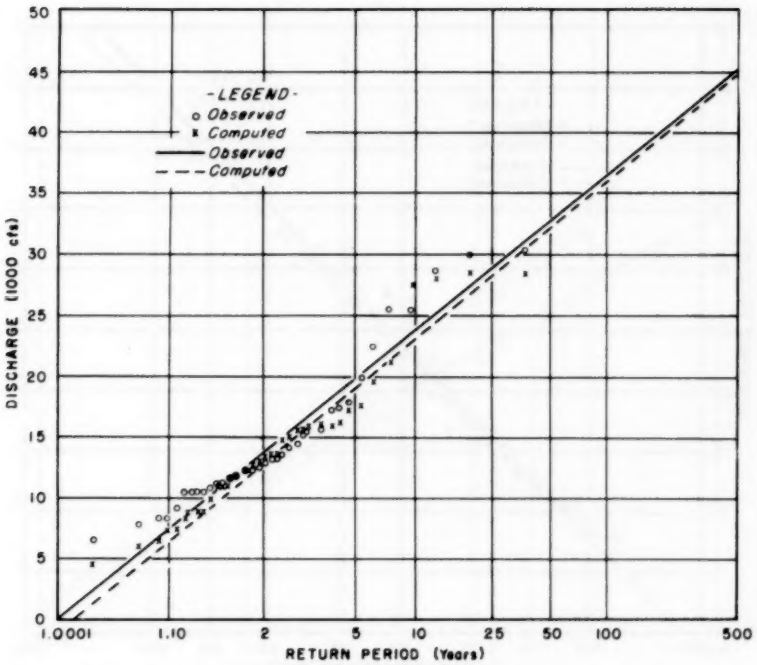

Figure 5. Comparison of computed and observed frequency curves for the period 1915 - 1951, Hocking River Athens, O.

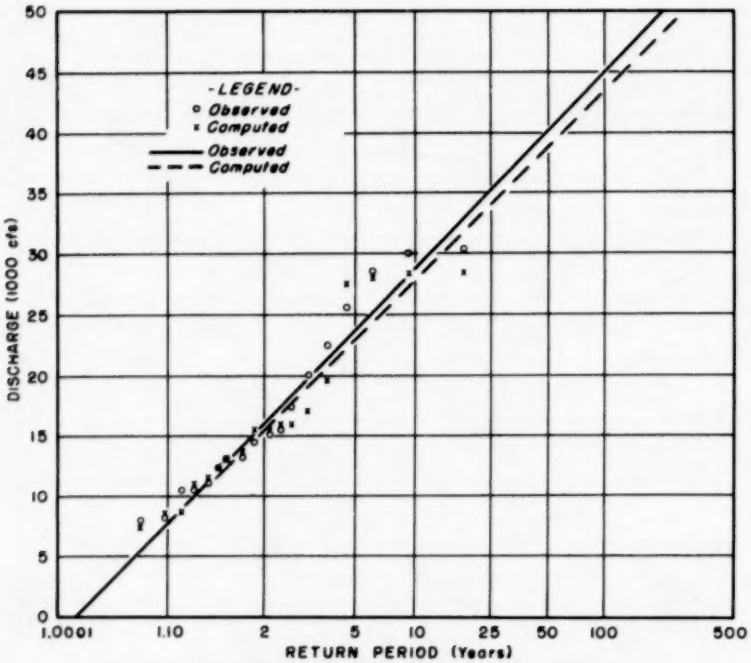

Figure 6. Comparison of computed and observed frequency curves for the period 1934 - 1951 Hocking River Athens, O.

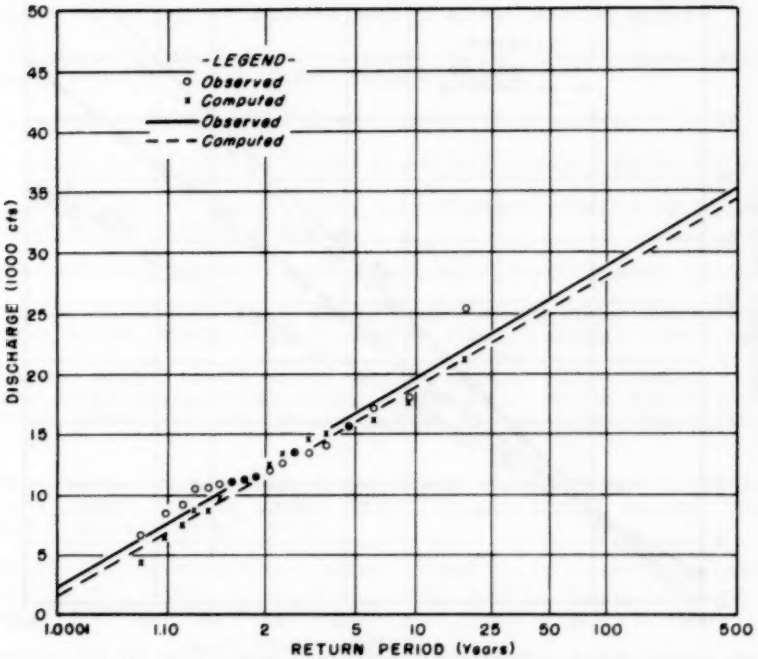

Figure 7. Comparison of computed and observed frequency curves for the period 1916 - 1933, Hocking River Athens, O.

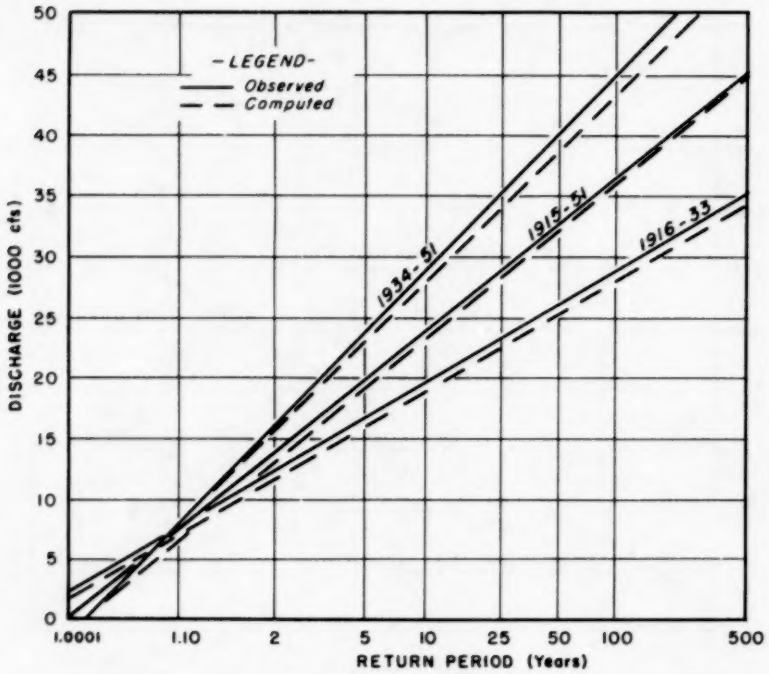

Figure 8. Comparison of computed and observed frequency curves for the periods 1915 - 1951, 1916 - 1933, 1934 - 1951 Hocking River Athens, O.

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OCTOBER: 512(SM), 513(SM), 514(SM), 515(SM), 516(SM), 517(PO), 518(SM)[c], 519(IR), 520(IR), 521(IR), 522(IR)[c], 523(AT)[c], 524(SU), 525(SU)[c], 526(EM), 527(EM), 528(EM), 529(EM), 530(EM)[c], 531(EM), 532(EM)[c], 533(PO).

NOVEMBER: 534(HY), 535(HY), 536(HY), 537(HY), 538(HY)[c], 539(ST), 540(ST), 541(ST), 542(ST), 543(ST), 544(ST), 545(SA), 546(SA), 547(SA), 548(SM), 549(SM), 550(SM), 551(SM), 552(SA), 553(SM)[c], 554(SA), 555(SA), 556(SA), 557(SA).

DECEMBER: 558(ST), 559(ST), 560(ST), 561(ST), 562(ST), 563(ST)[c], 564(HY), 565(HY), 566(HY), 567(HY), 568(HY)[c], 569(SM), 570(SM), 571(SM), 572(SM)[c], 573(SM)[c], 574(SU), 575(SU), 576(SU), 577(SU), 578(HY), 579(ST), 580(SU), 581(SU), 582(Index).

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JANUARY: 583(ST), 584(ST), 585(ST), 586(ST), 587(ST), 588(ST), 589(ST)[c], 590(SA), 591(SA), 592(SA), 593(SA), 594(SA), 595(SA)[c], 596(HW), 597(HW), 598(HW)[c], 599(CP), 600(CP), 601(CP), 602(CP), 603(CP), 604(EM), 605(EM), 606(EM)[c], 607(EM).

FEBRUARY: 608(WW), 609(WW), 610(WW), 611(WW), 612(WW), 613(WW), 614(WW), 615(WW), 616(WW), 617(IR), 618(IR), 619(IR), 620(IR), 621(IR)[c], 622(IR), 623(IR), 624(HY)[c], 625(HY), 626(HY), 627(HY), 628(HY), 629(HY), 630(HY), 631(HY), 632(CO), 633(CO).

c. Discussion of several papers, grouped by Divisions.
d. Presented at the Atlanta (Ga.) Convention of the Society in February, 1954.
e. Presented at the Atlantic City (N.J.) Convention in June, 1954.

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